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Karl D. Stephan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Massachusetts
Amherst, MA 01003

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13. ABSTRACT (Maximum 200 words)

Monolithic integration of microwave and millimeter-wave circuits means new techniques for using high-frequency devices in monolithic circuits must be developed. This report describes a series of several studies that address this need. A biasing technique for negative-resistance devices using a low-impedance lossy transmission line was found to be very useful in the design of planar oscillator circuits. This technique can be applied to monolithic circuits. Mutual impedance between elements in a quasioptical power combiner is often hard to calculate. A simple technique is described for obtaining this quantity experimentally. Power combining experiments and noise measurements involving resonant-tunneling diodes conclude the report.

14. SUBJECT TERMS

Microwave, millimeter wave, monolithic, oscillator, power combining, resonant tunneling diode, transmission line

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INTERINJECTION-LOCKED QUASIOPTICAL POWER COMBINERS AND PHASED ARRAYS

by

Karl D. Stephan

Final Technical Report
submitted to
U. S. Army Research Office
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Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA 01003

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I. Introduction

The advantages of planar, integrated, or monolithic fabrication for microwave and millimeter-wave circuits are too well known to be repeated here, except in summary form. The reduction in size, weight, and ultimately, manufacturing costs are strong forces driving the need for new approaches to circuit design, incorporating new devices when possible. Novel two-terminal devices in novel planar oscillator circuits were investigated during the term of this contract. We developed several experimental techniques for dealing with problems unique to these oscillators, and we broke new ground in the investigation and exploitation of resonant tunneling diodes.

II. Mutual Coupling of Planar Oscillators

Despite advances in numerical electromagnetic analysis software, many practical problems in antenna arrays and mutual coupling are still beyond the practical scope of computational analysis. An important category of problems is the case of an array of planar oscillators. Usually the desired mode of operation is for all the oscillators to work in phase, creating a beam that travels outward perpendicular to the plane of the oscillators. But in the absence of external reflectors or other synchronizing influences, the phase of each oscillator will be determined by the signals it receives from the others by means of mutual coupling. And this mutual coupling is a quantity that is not easily calculated except for simple ideal cases.

In working with monolithic IMPATT oscillators operating at 50 GHz, we realized how difficult it was to obtain data on the mutual impedance between oscillators on a ground plane. In response to this problem we developed a simple experimental technique to determine the imaginary part (X_{12}) of the mutual impedance between two oscillators [1]. As Fig. 1 shows, the method uses one oscillator and its mirror image. The effective distance between the real oscillator and its image is varied by moving the mirror. Tracking the oscillator's frequency as a function of mirror distance gives data that can be reduced to values of X_{12}, as shown in Fig. 2. This technique for measuring mutual impedance of planar oscillators has since been adopted by Robert York of U. C. Santa

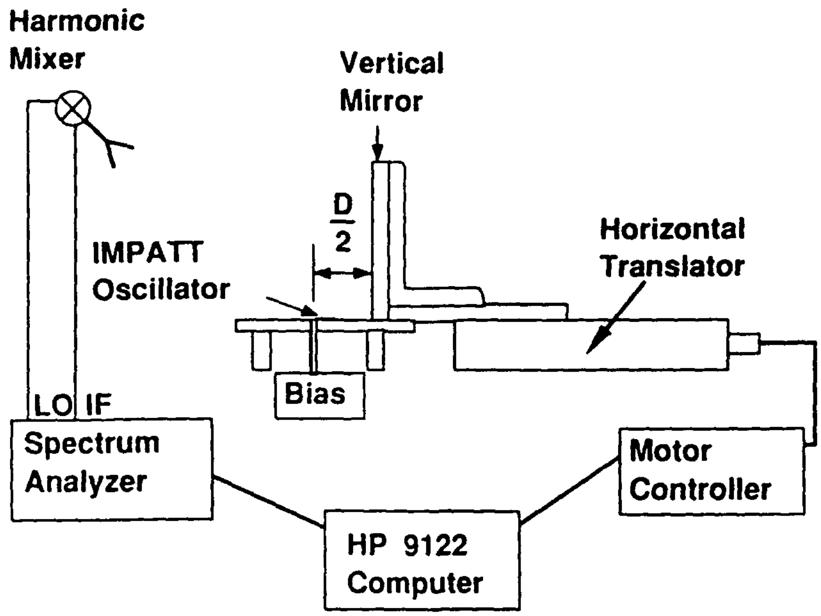

Fig. 1. Experimental setup for measurement of frequency variation versus separation distance between a single oscillator and a vertical mirror. (from Ref. [1])

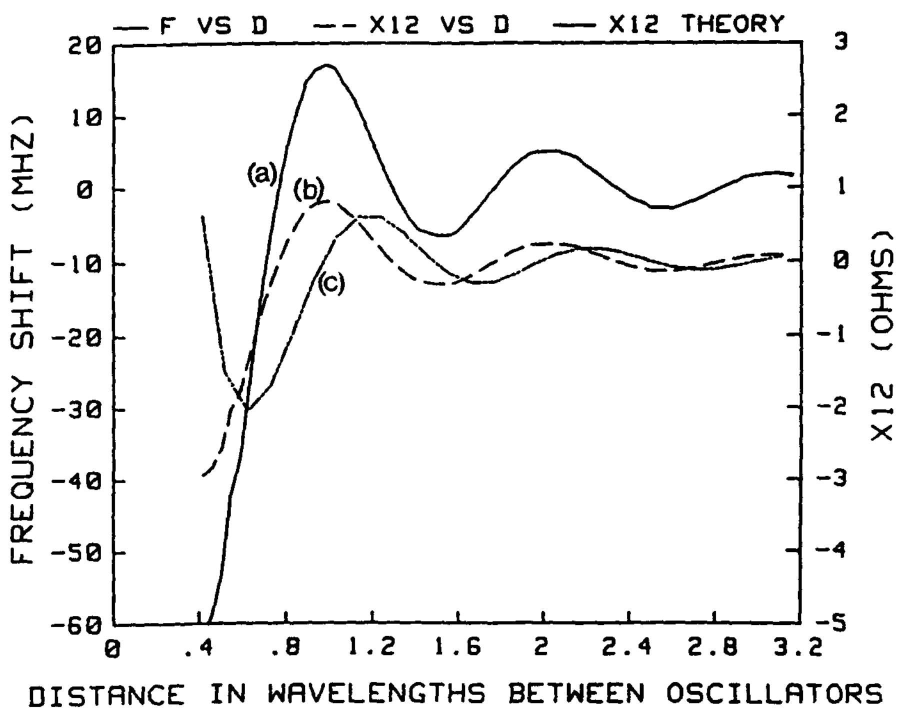

Fig. 2. (a) Measurement of Δf versus D (interoscillator spacing). (b) X_{12} versus D converted from frequency measurement. (c) X_{12} versus D derived from mutual impedance radiation model. (from Ref. [1])

Barbara and others.

III. Stabilization of Planar Oscillators

The word "stabilization" is used in this section in two different but related senses. The first meaning is "to prevent oscillation." A successfully stabilized circuit, in the first sense, is in the steady state with no tendency toward oscillation or other changes with time. We use the word in this sense to refer to certain circuits which prevent negative-resistance devices from oscillating at undesired frequencies. This subject is treated in the first division of this section, entitled "Undesired oscillation suppression."

The second sense of the word "stabilization" is used in reference to oscillators. In this sense, a perfectly stable oscillator would produce a mathematically exact sine wave. Stabilization of an oscillator, in the second sense, refers to steps taken to improve the spectral purity of its output. This subject is treated under the heading "Desired oscillation stabilization."

A. Undesired oscillation suppression

The successful use of negative-resistance two-terminal devices as oscillators depends on presenting the device with an embedding impedance that encourages oscillation at the desired frequency and discourages oscillation everywhere else in the frequency spectrum. The frequency range over which the embedding impedance must be considered is the range in which the device shows significant negative dynamic resistance. Some devices such as Gunn-effect diodes have only a narrow frequency range of negative resistance. Relatively simple circuit precautions can be taken to insure that these devices do not oscillate at audio or low RF frequencies as well as the desired microwave frequency. IMPATT diodes have a somewhat broader range of negative resistance, and thus require more careful bias circuit design. Unfortunately worst of all in this respect is the tunnel diode and its modern cousin the resonant tunneling diode (RTD). The dynamic negative resistance of these devices goes down to DC and extends continuously into the millimeter-wave frequency range for RTDs. If the unique high-frequency advantages of the RTD are to be utilized, methods must be developed to insure that the devices oscillate only at the high

frequency desired and nowhere else. This is not easy.

In work that began while the principal investigator was on sabbatical leave at MIT Lincoln Laboratories, we found that a low-impedance lossy transmission line is capable of presenting RTDs with the broadband low-resistance bias source that is required to suppress undesired oscillation. We reported this work in connection with a quasioptically-coupled slot antenna oscillator [2,3] shown in Fig. 3. The attraction of this bias method is that the kind of lossy transmission line used is relatively easy to integrate in a monolithic structure. This should make the job of integrating RTD oscillators into monolithic circuits much easier.

B. Desired oscillation stabilization

Turning now to the second type of stabilization, namely the purification of spectral output, we found that a quasioptical open resonator is well suited for the stabilization of planar negative-resistance-device oscillators. We first applied this technique [4] to the 50-GHz monolithic IMPATTs furnished by Texas Instruments, the same devices that were used in the mutual coupling experiments. Open resonators a few cm in length can exhibit unloaded Q's on the order of 10,000 to 100,000 in the millimeter-wave range. When a high-Q resonance of a quasioptical cavity is coupled properly to a planar oscillator, the spectrum improves markedly. Fig. 4 shows the experimental setup used for the IMPATT oscillator. Fig. 5 shows its spectrum when the load was an open waveguide, and Fig. 6 (to the same scale) shows the notable spectral improvement obtained when the oscillator was placed in a quasioptical cavity.

The next step was to apply the same basic technique to RTDs. This was first done in the 10-GHz range as described in Ref. [2] and shown in Fig. 3. This oscillator was described in more detail in a subsequent *Electronics Letters* paper [3]. E. R. Brown and colleagues later applied the principle to a waveguide-based RTD oscillator at 100 GHz in the experiment [5] shown in Fig. 7. Brown obtained spectral improvements even greater than those we achieved with IMPATT oscillators. Since an important application of RTD oscillators may be as local oscillators for receiving mixers, techniques that will improve their spectral performance may be very significant in the future.

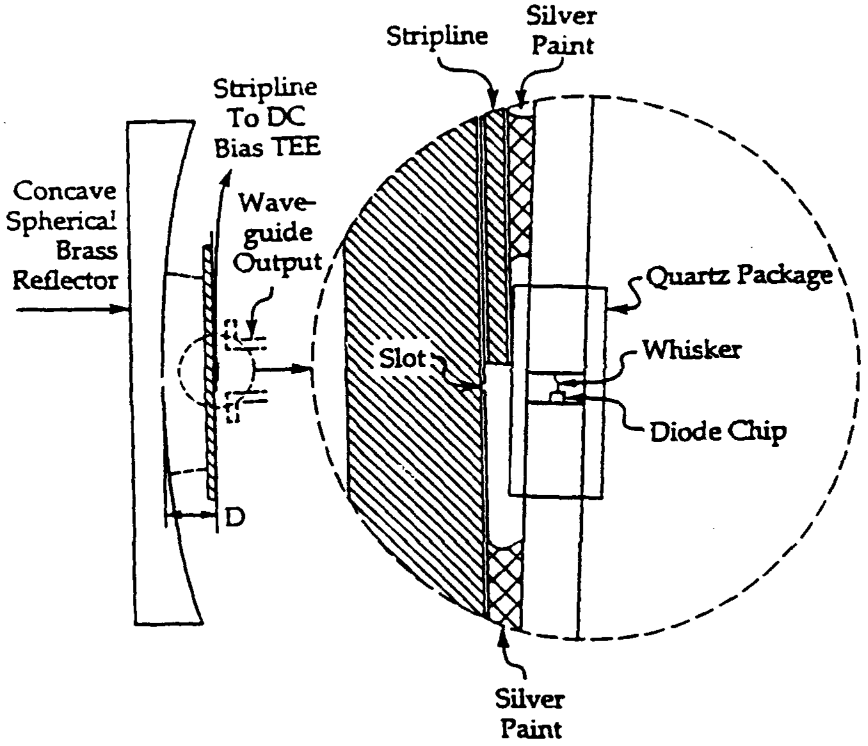

Fig. 3. Quasioptical cavity-stabilized oscillator at 8.9 GHz using lossy-line bias. (from Ref. [2])

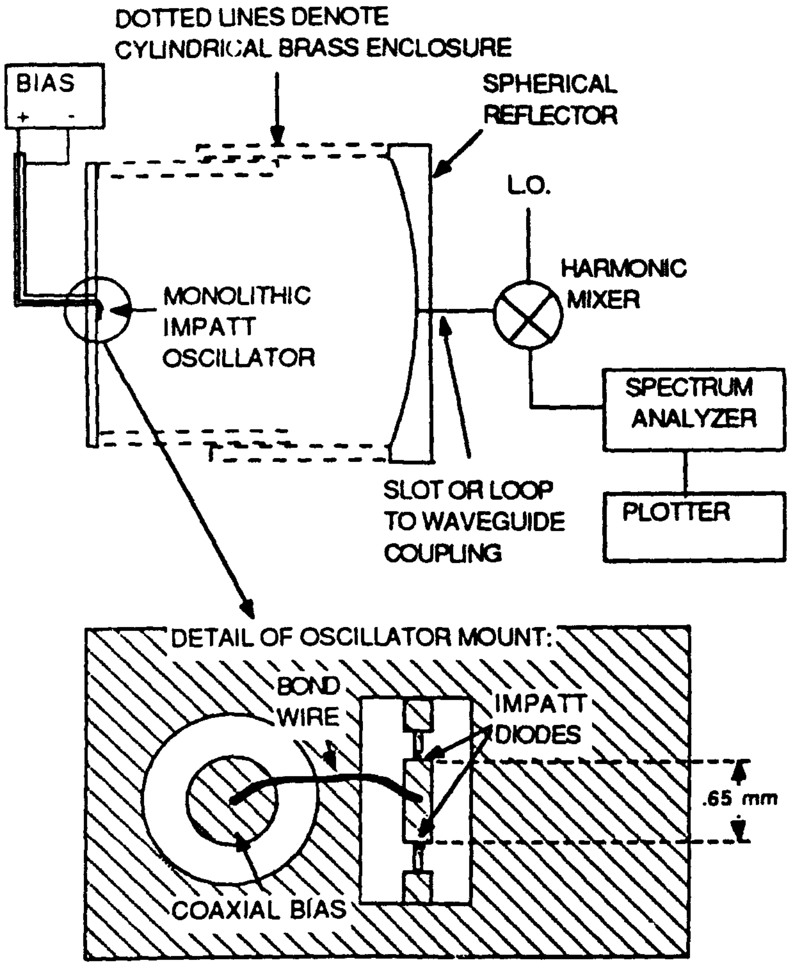

Fig. 4. Quasioptical cavity resonator containing monolithic IMPATT oscillator chip. (from Ref.[4])

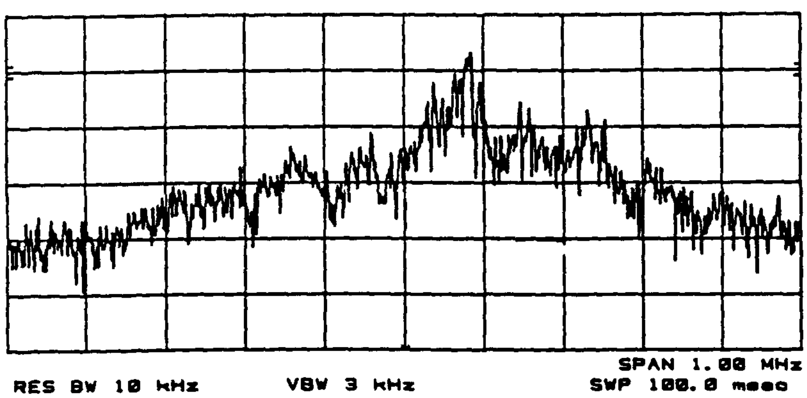

Fig. 5. Monolithic oscillator spectrum around center frequency of 56.031 GHz while operating into waveguide. (from Ref. [4])

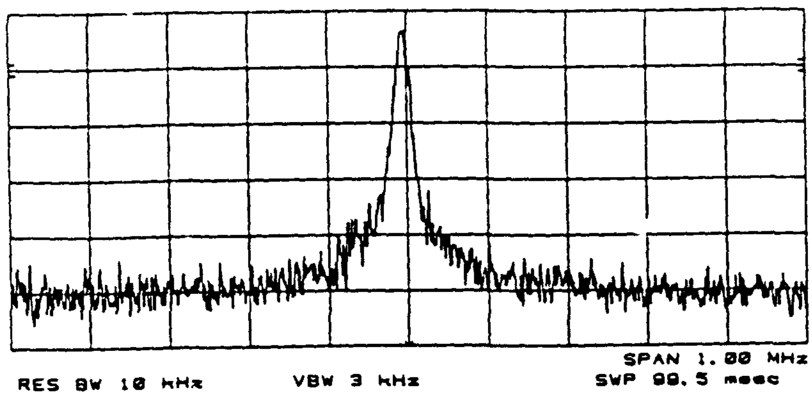

Fig. 6. Monolithic oscillator spectrum around center frequency of 56.097 GHz while operating in closed quasioptical cavity. (from Ref. [4])

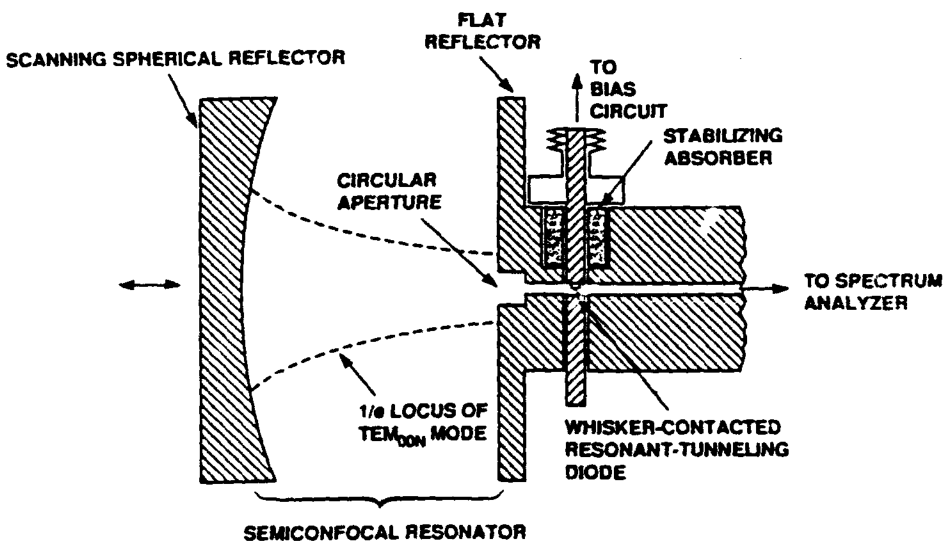

Fig. 7. Cross-sectional diagram of quasioptical RTD oscillator for 103 GHz. (from Ref. [5])

IV. Resonant tunneling diodes (RTDs)

After a long period during which tunnel diodes were eclipsed by more interesting and flexible three-terminal devices, the field has undergone something of a renaissance with the development of the resonant tunneling diode, or RTD. RTDs are made possible by fabrication techniques such as molecular-beam epitaxy and organometallic chemical vapor deposition which allow the precisely-controlled growth of semiconductor heterostructures having layers only a few atoms thick. The resulting quantum wells can be used for many purposes, among the simplest of which is the design of RTDs whose cutoff frequencies can approach 1 THz.

E. R. Brown and his colleagues at MIT Lincoln Laboratories have led the way in exploiting the high-frequency potential of these devices. During a sabbatical leave and the following collaboration, the principal investigator with his research assistants have explored two aspects of RTD applications, using devices supplied by MIT Lincoln Laboratories. These aspects will now be described.

A. Power combining of RTDs

Despite their high-frequency capabilities, individual RTDs have a rather small maximum power capability, often in the microwatt range. The reason for this is simple. In a typical RTD the useful range of dynamic negative resistance occurs at a bias voltage of 1-2 volts. High-frequency operation of the devices limits the total usable area, which means that thermal considerations restrict the maximum DC current to the low milliamp range. These two restrictions limit the maximum RF power obtainable from a single device, which can never exceed a fraction of the DC input power. This ceiling is usually less than a milliwatt for a single microwave RTD. For many applications, more power than this is desirable.

One way to increase the total power available from an RTD oscillator is to increase the number of devices used. In a collaborative experiment in which MIT Lincoln Laboratories supplied a set of 25 monolithically-paralleled RTDs, we demonstrated a power-combined output of 5 mW at around 1 GHz from this array [6]. The same kind of lossy-line bias method as discussed above was used in the oscillator bias circuit. At the time this work was reported, it represented one of the highest

power outputs ever obtained from a microwave RTD oscillator up to that time.

B. Noise in RTD Oscillators

As we mentioned earlier, applications of RTDs in local oscillator service will require the best possible spectral characteristics. Since the RTD is a fairly new device, relatively little is known about its noise characteristics. E. R. Brown has proposed a model [7] of shot noise in RTDs that predicts either enhancement or suppression of shot noise, depending on whether the device is operating in the negative-resistance or positive-resistance portion of its current-voltage characteristic, respectively. In recent experiments which are as yet unpublished, we have built a low-microwave-frequency RTD oscillator around a triple-barrier device furnished by MIT Lincoln Laboratories. Elaborate noise measurements using a phase-noise test setup have confirmed the basics of Brown's theory, but work was continuing at the expiration of this contract to understand the noise mechanism and the theory in more detail.

V. Conclusions

Basic research is by its very nature unpredictable, and the work just summarized has concentrated on areas somewhat different than those we planned to explore at the outset. For example, more activity involving three-terminal devices was originally anticipated, but not carried out. Nevertheless, we feel that many of the techniques and models developed will be useful regardless of the type of devices they will be used with in the future. The low-impedance lossy transmission line may be helpful in stabilizing three-terminal millimeter-wave devices as well as two-terminal ones. Open-resonator oscillator stabilization is a technique that can be applied to any kind of oscillator that can be coupled to a quasioptical resonator. Whatever the specific application, we feel that the results of this research contract have contributed significantly to the knowledge and technology base of the United States.

VI. List of Publications Under ARO Sponsorship

1. W. P. Shillue, S.-C. Wong, and K. D. Stephan. "Monolithic IMPATT oscillator stabilized by open cavity resonator," *1989 IEEE Int'l. Microwave Symp. Dig.*, pp. 739-740, Long Beach, Cal., June 1989.
2. K. D. Stephan and T. Itoh, "Recent efforts on planar components for active quasi-optical applications," *1990 IEEE Int'l. Microwave Symp. Dig.*, pp. 1205-1208, Dallas, Tex., May 1990.
3. W. P. Shillue and K. D. Stephan, "A technique for the measurement of mutual impedance of monolithic solid-state quasioptical oscillators," *Microwave and Optical Technology Letters*, vol. 3, pp. 414-416, Dec. 1990.
4. K. D. Stephan, S.-C. Wong, and E. R. Brown, "Lossy-line stabilization of negative-resistance diodes for integrated-circuit oscillators," *Proc. of the Second Int'l. Symposium on Space Terahertz Technology*, pp. 154-162, Pasadena, Cal., Feb. 26-28, 1991.
5. K. D. Stephan, E. R. Brown, C. D. Parker, W. D. Goodhue, C. L. Chen, and T. C. L. G. Sollner, "Resonant-tunnelling diode oscillator using a slot-coupled quasioptical open resonator," *Electronics Letters*, vol. 27, pp. 647--649, Apr. 11, 1991.
6. E. R. Brown, C. D. Parker, K. M. Molvar, and K. D. Stephan, "A quasioptically stabilized resonant-tunneling-diode oscillator for the millimeter- and submillimeter-wave regions," *IEEE Trans. on Microwave Theory and Tech.*, vol. 40, pp. 846-850, May 1992.
7. K. D. Stephan, S.-C. Wong, E. R. Brown, K. M. Molvar, A. R. Calawa, and M. J. Manfra, "5 mW parallel-connected resonant-tunnelling diode oscillator," *Electronics Letters*, vol. 28, pp. 1411-1412, July 16, 1992.

VII. List of Personnel Involved in Investigations Under ARO Sponsorship

1. Principal Investigator: Karl D. Stephan
2. Graduate Students (in chronological order):
   * Chong-Lap Woo — M. S., Univ. of Mass., May 1990
   * William P. Shillue — M. S., Univ. of Mass., Sept. 1990
   * Tung-Yi Wu — M. S., Univ. of Mass., Sept. 1992
   * Sai-Chu Wong — M. S., Univ. of Mass., Feb. 1992 (Ph. D. degree expected 1993)

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[1] W. P. Shillue and K. D. Stephan, "A technique for the measurement of mutual impedance of monolithic solid-state quasioptical oscillators," *Microwave and Optical Technology Letters*, vol. 3, pp. 414-416, Dec. 1990.

[2] K. D. Stephan, S C. Wong, and E. R. Brown, "Lossy-line stabilization of negative-resistance diodes ; r integrated-circuit oscillators," *Proc. of the Second Int'l. Symposium on Space Terahertz Technology*, pp. 154-162, Pasadena, Cal., Feb. 26-28, 1991.

[3] K. D. Stephan, E. R. Brown, C. D. Parker, W. D. Goodhue, C. L. Chen, and T. C. L. G. Sollner, "Resonant-tunnelling diode oscillator using a slot-coupled quasioptical open resonator," *Electronics Letters*, vol. 27, pp. 647-649, Apr. 11, 1991.

[4] W. P. Shillue, S.-C. Wong, and K. D. Stephan, "Monolithic IMPATT oscillator stabilized by open cavity resonator," *1989 IEEE Int'l. Microwave Symp. Dig.*, pp. 739-740, Long Beach, Cal., June 1989.

[5] E. R. Brown, C. D. Parker, K. M. Molvar, and K. D. Stephan, "A quasioptically stabilized resonant-tunneling-diode oscillator for the millimeter- and submillimeter-wave regions," *IEEE Trans. on Microwave Theory and Tech.*, vol. 40, pp. 846-850, May 1992.

[6] K. D. Stephan, S.-C. Wong, E. R. Brown, K. M. Molvar, A. R. Calawa, and M. J. Manfra, "5 mW parallel-connected resonant-tunnelling diode oscillator," *Electronics Letters*, vol. 28, pp. 1411-1412, July 16, 1992.

[7] E. R. Brown, "Analytic model of shot noise in double-barrier resonant-tunneling diodes," *IEEE Trans. on Electron Devices*, vol. 39, pp. 2686-2693, Dec. 1992.